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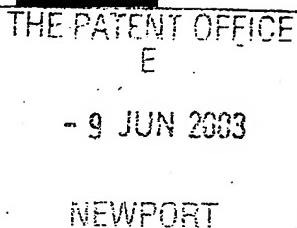
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PATHFINDER ENERGY SERVICES, Inc.
15151 Somermeyer St
Houston, Texas 77041, USA

86491 oSODI

Patents ADP number *(if you know it)*

If the applicant is a corporate body, give the country/state of its incorporation

Louisiana, U.S.A.

4. Title of the invention

Well Twinning Techniques in Borehole Surveying

5. Name of your agent *(if you have one)*

URQUHART-DYKES & LORD

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Three Trinity Court
21-27 Newport Road
CARDIFF
CF24 0AA

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Urquhart-Dykes & Lord Signature

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Date

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12. Name and daytime telephone number of person to contact in the United Kingdom

Karen Cawdell

029 2048 7993

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WELL TWINNING TECHNIQUES IN BOREHOLE SURVEYING

The present invention relates generally to surveying a

5   subterranean borehole to determine, for example, the path of

the borehole. More particularly this method relates to a

method of passive ranging to determine directional and/or

locational parameters of a borehole using sensors including

one or more magnetic field measurement devices.

10

The use of magnetic field measurement devices (e.g.,

magnetometers) in prior art subterranean surveying techniques

for determining the direction of the earth's magnetic field at

a particular point is well known. The use of accelerometers

15   or gyroscopes in combination with one or more magnetometers to

determine direction is also known. Deployments of such sensor

sets are well known to determine borehole characteristics such

as · inclination, azimuth, positions in space, tool face

rotation, magnetic tool face, and magnetic azimuth (i.e., an

20   azimuth value determined from magnetic field measurements).

While magnetometers are known to provide valuable information

to the surveyor, their use in borehole surveying, and in

particular measurement while drilling (MWD) applications,

tends to be limited by various factors. For example, magnetic

25   interference, such as from the magnetic steel components

(e.g., liners, casings, etc.) of an adjacent borehole (also

referred to as a target well herein) tends to interfere with

the earth's magnetic field and thus may cause a deflection in the azimuth values obtained from a magnetometer set.

Passive ranging techniques may utilize such magnetic interference fields, for example, to help determine the location of an adjacent well (target well) to reduce the risk of collision and/or to place the well into a kill zone (e.g., near a well blow out where formation fluid is escaping to an adjacent well). U.S. Patent 5,675,488 and U.S. Patent Applications 10/368,257 and 10/369,353 to McElhinney (herein referred to as the McElhinney patents) describe methods for determining the position of a target well with respect to a measured well (e.g., the well being drilled) in close proximity thereto. Such methods utilize three-dimensional magnetic interference vectors determined at a number of points in the measured well to determine azimuth and/or inclination of the target well and/or the distance from the measured well to the target well.

The methods described in the McElhinney patents have been shown to work well in a number of borehole surveying applications, such as, for example, well avoidance and or well kill applications. However, there remain certain other applications for which improved passive ranging techniques may advantageously be utilized. For example, well twinning applications (in particular in near horizontal well sections),

in which a measured well is drilled essentially parallel to a target well, may benefit from such improved passive ranging techniques. Therefore, there exists a need for improved borehole surveying methods utilizing various passive ranging

5 techniques.

In one aspect the present invention includes a method for surveying a borehole. The method includes providing a downhole tool including first and second magnetic field

10 measurement devices disposed at corresponding first and second positions in the borehole. The first and second positions are selected to be within sensor range of magnetic flux from a target subterranean structure. The method further includes measuring total local magnetic fields at the first and second

15 positions using the corresponding first and second magnetic field measurement devices, processing the total local magnetic fields at the first and second positions to determine a portion of the total local magnetic fields attributable to the target subterranean structure, and generating interference

20 magnetic field vectors at the first and second positions from the portion of the total local magnetic field attributable to the target subterranean structure. The method further includes processing the interference magnetic field vectors to determine tool face to target values at the first and second

25 positions. One variation of this aspect further includes providing a historical survey of at least a portion of the

target subterranean structure and processing the tool face to

target values at the first and second positions and the

historical survey to determine a distance from the borehole to

the target subterranean structure. This variation of this

.5   aspect further includes processing the distance and the

historical survey to determine a location of either the first

or second positions and utilizing the location to determine a

borehole azimuth.

10   The foregoing has outlined rather broadly the features and

technical advantages of the present invention in order that

the detailed description of the invention that follows may be

better understood. Additional features and advantages of the

invention will be described hereinafter which form the subject

15   of the claims of the invention. It should be appreciated by

those skilled in the art that the conception and the specific

embodiment disclosed may be readily utilized as a basis for

modifying or designing other structures for carrying out the

same purposes of the present invention. It should be also be

20   realize by those skilled in the art that such equivalent

constructions do not depart from the spirit and scope of the

invention as set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

25   For a more complete understanding of the present invention,

and the advantages thereof, reference is now made to the

following descriptions taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is a schematic representation of an exemplary embodiment of a MWD tool according to the present invention

5   including both upper and lower sensor sets.

FIGURE 2 is a diagrammatic representation of a portion of the MWD tool of FIGURE 1 showing unit magnetic field and gravity vectors.

FIGURES 3A and 3B are schematic representations of an

10 exemplary application of this invention.

FIGURE 4 is a schematic representation of a cross sectional view along section 4-4 of FIGURE 3B.

FIGURE 5 is a schematic representation of a hypothetical plot of tool face to target versus well depth as an illustrative

15 example of one embodiment of this invention.

FIGURE 6 is a schematic representation of a cross sectional view similar to that of FIGURE 4.

FIGURE 7 is a graphical representation of tool face to target versus measured depth, similar to the hypothetical plot of

20 FIGURE 5, for a portion of an exemplary borehole survey conducted according to exemplary embodiments of this invention.

FIGURE 8 is a graphical representation of azimuth and distance versus measured depth for another portion of the survey shown

25 in FIGURE 7.

FIGURE 9 is a graphical representation of tool face to target

versus measurement number for a portion of a field test conducted according to exemplary embodiments of this invention.

FIGURE 10 is a graphical representation of delta tool face to

5 target and the dip of the magnetic interference vector versus measurement number for the field test shown in FIGURE 9.

FIGURE 11 is another diagrammatic representation of a portion of the MWD tool of FIGURE 1 showing the change in azimuth between the upper and lower sensor sets.

10

Referring now to FIGURE 1, one exemplary embodiment of a downhole tool 100 useful in conjunction with the method of the present invention is illustrated. In FIGURE 1, downhole tool 100 is illustrated as a measurement while drilling

15 (MWD) tool including upper 110 and lower 120 sensor sets coupled to a bottom hole assembly (BHA) 150 including, for example, a steering tool 154 and a drill bit assembly 158. The upper 110 and lower 120 sensor sets are disposed at a known spacing, for example, on the order of from about 2 to

20 about 20 meters (i.e., about 6 to about 60 feet). Each sensor set (110 and 120) includes at least three mutually orthogonal magnetic field sensors, with at least one magnetic field sensor in each set having a known orientation with respect to the borehole, and three mutually orthogonal

25 gravity sensors. It will be appreciated that the method of this invention may be practiced with a downhole tool

including only a single sensor set having at least two

magnetic field sensors. No gravity measurement sensors are

required.

5   Referring now to FIGURE 2, a diagrammatic representation of a

portion of the MWD tool of FIGURE 1 is illustrated. In the

embodiment shown on FIGURES 1 and 2, each sensor set includes

three mutually perpendicular magnetic field sensors, one of

which is oriented substantially parallel with the borehole and

10   measures magnetic field vectors denoted as Bz1 and Bz2 for the

upper 110 and lower 120 sensor sets, respectively. The upper

110 and lower 120 sensor sets are linked by a structure 140

(e.g., a semi-rigid tube such as a portion of a drill string)

that permits bending along its longitudinal axis 50, but

15   substantially resists rotation between the upper 110 and lower

120 sensor sets along the longitudinal axis 50. Each set of

magnetic field sensors thus may be considered as determining a

plane (Bx and By) and pole (Bz) as shown. As described in

more detail below, embodiments of this invention typically

20   only require magnetic field measurements in the plane of the

tool face (Bx and By as shown in FIGURE 2 which corresponds

with plane 121, for example, in sensor set 120). The

structure 140 between the upper 110 and lower 120 sensor sets

may advantageously be part of, for example, a MWD tool as

25   shown above in FIGURE 1. Alternatively, structure 140 may be

a part of substantially any other logging and/or surveying

apparatuses, such as a wireline surveying tool.

As described above, embodiments of this invention may be particularly useful, for example, in well twinning applications (e.g., relief well drilling), such as that shown in FIGURES 3A and 3B. In FIGURE 3A, a bottom hole assembly 150 is kicked off out of a casing window 178 in a pre-existing borehole 175. "Kicking off" refers to a quick change in the angle of a borehole, and may be associated, for example with drilling a new hole from the bottom or the side of an existing borehole. A relief well 177, for example, is then drilled substantially parallel with the pre-existing borehole 175, as shown in FIGURE 3B. In such applications there tends to be significant magnetic interference emanating from the pre existing borehole 175, e.g., from the well casing, owing, for example, to residual magnetization from magnetic particle inspection procedures. Normally, such magnetic interference fades (decreases) quickly as the distance to the pre-existing borehole increases. However, in well relief applications, for example, in which the distance between the relief well 177 and the pre-existing borehole 175 typically remains small (e.g., from about 1 to about 10 feet), such magnetic interference tends to significantly interfere with the determination of borehole azimuth using conventional magnetic surveying techniques. Further, such relief well drilling applications are often carried out in near horizontal wells (e.g., to

divert around a portion of a pre-existing borehole that has collapsed). Thus conventional gyroscope and gravity azimuth surveying methods may be less than optimal for borehole surveying in such applications. As described in more detail below, this invention may utilize the magnetic interference from a target well (e.g., pre-existing borehole 175) to determine the azimuth of the measured well (e.g., relief well 177). Surveying according to the present invention may thus be useful in such relief well and/or well twinning applications.

It should be noted that the magnetic interference may emanate from substantially any point or points on the target well. It may also have substantially any field strength and be oriented at substantially any angle to the target well, with the field strength at a particular location generally decreasing with distance from the target borehole. Further, the magnetic interference tends to be caused by the tubular elements in the target well, e.g., the casing, drill string, collars, and the like. The magnetic interference surrounding these elements is determined by the magnetism (both induced and permanent) in the metal. The shape of the interference pattern is particularly influenced by the homogeneity of the magnetism and the shape of the metal element. Typically, the magnetism is substantially homogeneous and the shape rotationally symmetrical and tubular. Objects in a borehole, such as pipe

sections and the like, are often threadably coupled to form a substantially continuous cylinder. Thus, the origin of any magnetic interference emanating from a borehole may generally be considered to originate in cylinders therefrom. The

5   magnetic field emanating from such a borehole (target well) is typically caused by such cylinders in a manner typically displayed by cylindrical magnets. Such is the basis for the passive ranging techniques disclosed in the McElhinney patents.

10

The magnetic interference may be measured as a vector whose orientation depends on the location of the measurement point within the magnetic field. In order to determine the magnetic interference vector at any point downhole, the

15   magnetic field of the earth must be subtracted from the measured magnetic field vector. The magnetic field of the earth (including both magnitude and direction components) is typically known, for example, from previous geological survey data. However, for some applications it may be advantageous

20   to measure the magnetic field in real time on site at a location substantially free from magnetic interference, e.g., at the surface of the well or in a previously drilled well. Measurement of the magnetic field in real time is generally advantageous in that in that it accounts for time dependent

25   variations in the earth's magnetic field, e.g., as caused by solar winds. However, at certain sites, such as on an

offshore drilling rig, measurement of the earth's magnetic
field in real time may not be possible. In such instances, it
may be preferable to utilize previous geological survey data
in combination with suitable interpolation and/or mathematical

5   modeling (i.e., computer modeling) routines.

The earth's magnetic field at the tool may be expressed as
follows:

10    $$M_{EX} = H_E(\cos D \sin Az \cos R + \cos D \cos Az \cos Inc \sin R - \sin D \sin Inc \sin R)$$

$$M_{EY} = H_E(\cos D \cos Az \cos Inc \cos R + \sin D \sin Inc \cos R - \cos D \sin Az \sin R)$$

$$M_{EZ} = H_E(\sin D \cos Inc - \cos D \cos Az \sin Inc) \qquad \text{Equation 1}$$

where Mex, Mey, and Mez represent the x, y, and z components,
15   respectively, of the earth's magnetic field as measured at the
downhole tool, where the z component is aligned with the
borehole axis, He is known (or measured as described above)
and represents the magnitude of the earth's magnetic field,
and D, which is also known (or measured), represents the local
20   magnetic dip. Inc, Az, and R, represent the Inclination,
Azimuth and Rotation (also known as the gravity tool face),
respectively, of the tool, which may be obtained, for example,
from conventional gravity surveying techniques. However, as
described above, in various relief well applications, such as
25   in near horizontal wells, azimuth determination from
conventional surveying techniques tends to be unreliable. In
such applications, since the measured borehole and the target
borehole are essentially parallel (i.e., within a five or ten
degrees of being parallel), Az values from the target well, as
30   determined, for example in a historical survey, may be

utilized.

The magnetic interference vectors may then be represented as
follows:

$$M_{IX} = B_X - M_{EX}$$

$$M_{IY} = B_Y - M_{EY}$$

$$M_{IZ} = B_Z - M_{EZ} \qquad\qquad \text{Equation 2}$$

where Mix, Miy, and Miz represent the x, y, and z components,
respectively, of the magnetic interference vector and Bx, By,
and Bz, as described above, represent the measured magnetic
field vectors in the x, y, and z directions, respectively.

The artisan of ordinary skill will readily recognize that in
determining the magnetic interference vectors it may also be
necessary to subtract other magnetic field components, such as
drill string and/or motor interference from the borehole being
drilled, from the measured magnetic field vectors.

Referring now to FIGURES 4 through 11, embodiments of the
method of this invention are described in further detail.
With reference to FIGURE 4, a cross sectional representation
of section 4-4 in FIGURE 3B is shown looking down the target
borehole 175. Since the measured borehole and the target
borehole are approximately parallel, the view of FIGURE 4 is
also essentially looking down the measured borehole. The
magnetic flux lines 202 emanating from the target borehole 175
are shown to substantially intersect the target borehole 175

at a point T.   Thus a magnetic field vector 205 determined at
the measured borehole 177, for example, as determined by
Equations 1 and 2 above, provides a direction from the
measured borehole to the target borehole 175.   Since the
5   measured borehole and the target borehole are essentially
parallel, determination of a two dimensional magnetic field
vector (e.g., in the planes of the tool faces 111 and 121
shown in FIGURE 2) is sufficient for determining the direction
from the measured well to the target well.

10

A tool face to target (TFT) value may be determined from the
magnetic interference vectors given in Equation 2 as follows:

$$TFT = \arctan(\frac{M_{IX}}{M_{IY}}) \qquad\qquad \text{Equation 3}$$

15   where TFT represents to tool face to target direction (angular
orientation) and Mix and Miy represent the x and y components,
respectively, of the magnetic interference vector.   As shown
in FIGURE 4, the TFT indicates the direction from the measured
well 177 to the target well 175.   For example, a TFT of 90
20   degrees, as shown in FIGURE 4, indicates that the target well
175 is directly to the right of the measured well 177.   A TFT
of 270 degrees, on the other hand, indicates that the target
well is directly to the left of the measured well.   Further,
at TFT values of 0 and 180 degrees the target well 175 is

directly above and directly below, respectively, the measured well 177.

In certain applications determination of the TFT at two or more points along the measured well bore may be sufficient to guide continued drilling of the measured well, for example, in a direction substantially parallel with the target well. This is shown schematically in FIGURE 5, which shows a schematic representation of a plot 250 of TFT 252 versus Well Depth 254. Data sets 262, 264, 266, and 268 represent TFT values determined at various well depths. Each data set, e.g., data set 262, includes two data points, A and B, determined at a single survey location (station). In data set 262, for example, data point A is the TFT value determined from the magnetic interference vector measured at an upper sensor set (e.g., sensor set 110 in FIGURES 1 through 3B) and data point B is the TFT value determined from the magnetic interference vector measured at a lower sensor set (e.g., sensor set 120 in FIGURES 1 through 3B), which resides some fixed distance (e.g., from about 6 to about 60 feet) further down the borehole than the upper sensor set. Thus at each survey station (data sets 262, 264, 266, and 268) two magnetic interference vectors may be determined. The TFT at each data point indicates the direction to the target borehole from that point on the measured borehole. Additionally, and advantageously for MWD embodiments including two sensor sets,

comparison of the A and B data points in a given data set (e.g., set 262) indicates the relative direction of drilling with respect to the target well at the location of that data set. Further, since a drill bit is typically a known distance

5   below the lower sensor set, the TFT at the drill bit may be determined by extrapolating the TFT values from the upper and lower sensor sets (points A and B on FIGURE 5).

With continued reference to FIGURE 5, data sets 262, 264, 266,

10 and 268 are described in more detail. In this hypothetical example, data sets 262, 264, 266, and 268 represent sequential survey stations (locations) during an MWD drilling operation and thus may be spaced at a known interval (e.g., about 50 feet) in the measured well. At data set 262, the target well

15 is down and to the right of the measured well as indicated by the TFT values. Since the TFT at point B is closer to 90 degrees than that of point A, data set 262 indicates that the measured well is pointing downward relative to the target well. For a drilling operation in which it is intended to

20 drill the measured well parallel and at the same vertical depth as the target well, for example, data set 262 would indicate that drilling should continue for a time in approximately the same direction. At data set 264, the measured well has moved below the target well as indicated by

25 TFT values below 90 degrees. Similar TFT values for points A and B indicate that the measured MWD tool (and therefore the

measured well) is pointed horizontally relative to the target well. At data set 266, the measured well remains below the target well, but is pointing upward relative thereto. And at data set 268, the measured well is at about the same vertical

5 depth as the target well and substantially aligned therewith vertically.

While TFT values determined from the magnetic interference vectors provide potentially valuable directional information

10 relating to the position of a measured well relative to a target well, they do not, alone, provide an indication of the distance from the measured well to the target well. According to one aspect of this invention, the TFT valves may be utilized, along with a historical survey of the target well,

15 to determine a distance from the measured well to the target well. As described in more detail below, the direction and distance from the measured well to the target well may then be utilized to determine absolute coordinates and azimuth values for the measured well at various points along the length

20 thereof.

Referring now to FIGURE 6, a view down the target borehole similar to that of FIGURE 4 is shown. The measured borehole 177, as shown, is slightly downward and to the left of the

25 target borehole 175 as indicated by the TFT value being less than 90 degrees. In order to determine the distance, d,

between the measured 177 and target 175 boreholes it is assumed that the two boreholes have substantially equivalent vertical depths (e.g., equivalent total vertical depths in world coordinates). This is represented in FIGURE 6 by target

5 well 175'. As described in more detail below this assumption introduces minimal error when the two boreholes are aligned within about 10 degrees of one another, which is generally a valid assumption for typical well twinning and relief well applications, such as those described above with respect to

10 FIGURES 3A and 3B.

The distance from the measured well to the target well may be expressed mathematically as follows:

$$d = \frac{\Delta y}{\sin(\Delta TFT)} = \frac{\Delta y}{\cos(TFT)} \qquad\qquad \text{Equation 4}$$

15 where d represents the distance between the measured and target boreholes, Δy represents a change in the vertical position of the target well between first and second survey points, ΔTFT represents the change in the tool face to target values between the first and second survey points, and TFT

20 represents the tool face to target value at the second survey point. Δy may typically be determined from historical survey data for the target well, for example, obtained via gyroscope or other conventional surveying methodologies in combination with known interpolation techniques as required.

25

With the determination of the direction (i.e., TFT or ΔTFT) and the distance from the measured borehole to the target borehole at various points along the measured borehole it is possible to determine the location (i.e., the absolute coordinates) of those points on the measured borehole based on historical survey data for the target well. ·The location at each surveyed point on the measured borehole is given as follows:

$$PMx = PTx - d\sin(TFT) = PTx - d\cos(\Delta TFT)$$
$$PMy = PTy - d\cos(TFT) = PTy - d\sin(\Delta TFT)$$

Equation 5

where PMx and PMy represent the x and y coordinates, respectively, of the location of a point on the measured borehole, PTx and PTy represent x and y coordinates, respectively, of a corresponding point on the target borehole, and d, TFT, and ΔTFT are defined above with respect to Equation 4.

Once the coordinates of the of the measured borehole has been determined at at least two points therealong, determination of azimuth values for the measured borehole is straight forward and is given as follows:

$$AzM = \arctan(\frac{\Delta PMy}{\Delta PMx})$$

Equation 6

where AzM represents the azimuth at a point on the measured borehole,

$$\Delta PMx = PMx2 - PMx1$$
$$\Delta PMy = PMy2 - PMy1$$

Equation 7

and where PMx1, PMx2, PMy1, and PMy2 represent the x and y coordinates, respectively for adjacent survey points along the measured borehole. Inclination values, may be determined, for example, from conventional surveying methodologies, such as via gravity sensor measurements (as described in more detail below).

Referring now to Table 1 and FIGURES 7 and 8, exemplary methods of the present invention are discussed further by way of an actual field test example utilizing an MWD tool similar to that described above with respect to FIGURE 1 to guide drilling of a relief well essentially parallel with and at about the same vertical depth as an existing target well. The target well was essentially horizontal (having an inclination greater than 80 degrees) and oriented at an azimuth ranging from about 168 to about 173 degrees. With reference to Table 1, a portion of an exemplary survey conducted at a measured depth ranging from about 16,100 to about 16,600 feet is illustrated. At survey points 1 through 10, the gravity and magnetic fields were measured at upper and lower sensor sets. The upper sensor set was disposed about 16 feet above the lower sensor set and the survey points were spaced at about 50 foot intervals. Tool face to target (TFT) values were

determined from the magnetic interference vectors at each survey point. The distances from the measured well to the target well were also measured at various survey points and were utilized to determine absolute coordinates and azimuth values at those points on the measured well as shown. Inclination values for the measured well were determined via conventional gravity vector measurements as in more detail below.

Survey	Sensor Set	Depth (ft)	TFT	Distance (ft)	Inclination	Azimuth
	1	16,144	269		80.8	
1	2	16,160	279		80.9	
	1	16,194	246		81.8	
2	2	16,210	255	0.6	82.4	171
	1	16,241	256		83.8	
3	2	16,257	254		84.4	
	1	16,290	273	1.1	84.5	172
4	2	16,306	268	1.4	85.2	172
	1	16,335	256	3.0	86.7	174
5	2	16,351	255	3.2	87.2	172
	1	16,385	269		87.1	
6	2	16,401	269		87.3	
	1	16,429	270	5.0	87.7	172
7	2	16,445	271		88.4	
	1	16,480	270		88.8	
8	2	16,496	266		89.0	
	1	16,556	238		88.6	
9	2	16,572	253	3.5	88.9	168
	1	16,574	242	3.0	88.6	168
10	2	16,590	253		88.7	

Table 1

Referring now to FIGURES 7 and 8, the data in Table 1 is discussed in more detail. FIGURE 7 is a plot of tool face to target versus well depth. As described above, with respect to

FIGURE 5, the tool face to target data in FIGURE 7 indicate
the direction from the measured well to the target well at
various points along the measured well. As also described
above, the direction in which the measured well is pointing,

5   relative to the target well, is indicated at each survey
station.   For example, at the second survey station the
measured well was positioned above the target well and point
relatively downward.   Likewise at survey station 6, the
measured well was positioned approximately level with the

10   target well and pointing substantially level therewith.

FIGURE 8 is a plot of azimuth for both the measured and target
wells on one axis and the distance between the measured and
target wells on the other axis versus well depth.   The azimuth

15   values for the target well is shown at 302 and was obtained
from a historical survey thereof.   The azimuth values for the
measured well are shown at 304.   The distances between the
measured and target wells are shown at 306.   Both the azimuth
values for the measured well 304 and the distances 306 between

20   the measured and target wells are also shown in Table 1 and
were determined according to embodiments of this invention.
At measured depths from about 16,100 to about 16,250 feet, the
azimuth values for the measured and target wells were nearly
identical, indicating that the measured well was closely

25   paralleling the target well (as is desirable for various
relief well applications).   The relatively small distance

between the two wells (about a foot) further confirms that the measured well was closely paralleling the target well. At a measured depth from about 16,300 to about 16,350 feet the azimuth of the measured well increased to about three degrees

5   greater than that of the target well (about 174 versus about 171 degrees), indicating that the measured well was drifting slightly out of parallel with the target well. This is confirmed by the increased distance between the two wells (up to about five feet at a depth of 16,400 feet). The azimuth of

10   the measured well was then corrected, based on the data from this survey, and the distance between the two wells reduced to about three feet (at a depth of about 16,600 feet.

Based on the data shown in this example in Table 1 and FIGURES

15   7 and 8 it can be seen that embodiments of this invention include a method for drilling a relief well (or a method for twinning a well) that includes utilizing the surveying techniques described herein to guide the drill string (the measured well) along a predetermined course substantially

20   parallel with a target well. For example, as described above, an operator may utilize plots of tool face to target values versus well depth to adjust the vertical component of the drilling direction. Likewise a comparison of the azimuth values for the measured and target wells may be utilized to

25 · adjust the azimuthal (lateral) component of the drilling direction. Such a procedure enables the position of a

measured well to be determined relative to the target well in substantially real time, thereby enabling the drilling direction to be adjusted to more closely parallel the target well.

5

In determining the magnetic interference vectors, the distance between the measured and target wells, and the azimuth of the measured well, it may be advantageous in certain applications to employ one or more techniques to minimize or eliminate the

10 effect of erroneous data. For example, it may be advantageous to apply statistical methods to eliminate outlying points, for example, removing points that are greater than some predetermined deviation away from a previously measured point. Thus for example, if the distance between two wells is 3 feet

15 at a first survey point, a distance of 23 feet may be rejected at a second survey point. In certain instances it may also be desirable to remove individual interference vectors from the above analysis. For example, an interference vector may be removed when the magnitude of the interference magnetic field

20 vector is less than some minimum threshold (e.g., 0.001 Gauss).

An alternative, and optional, technique for minimizing error and reducing the effect of erroneous data is to make multiple

25 magnetic field measurements at each survey station. For example, magnetic field measurements may be made at multiple

tool face settings (e.g., at 0, 90, 180, and 270 degrees) at each survey station in the measured well bore. Such rotation of the tool face, while effecting the individual magnetometer readings (i.e., Bx and By), does not effect the interference

5 magnetic field, the tool face to target, the distance between the two wells, or the azimuth of the measured well.

Referring now to FIGURE 9, a plot of tool face to target versus measurement number is shown for a field test in which a

10 section of magnetized casing was placed substantially horizontally on the ground as a hypothetical target well. A hypothetical measured well was disposed nearby at a known position and orientation relative to the casing. A single set of magnetometers was utilized to measure the magnetic field at

15 points (stations) along the hypothetical measured well. Magnetic interference vectors and tool face to target values were determined at each point as described above. At numerous points, the set of magnetometers was rotated to four distinct orientations (0, 90, 180, and 270 degrees) as described above.

20 The tool face to target values determined via embodiments of this invention were compared to hand measured values. FIGURE 9 shows excellent agreement between the tool face to target values determined via embodiments of the passive ranging techniques of this invention and the hand measured values.

25

FIGURE 9 further shows, in this particular example, that at intermediate distances (e.g., from about 2 to about 20 feet shown in measurement points 10 through 50), highly accurate tool face to target values may be obtained from a measurement of the magnetic field at a single tool face setting. At very small distances (less than about 1 or 2 feet shown in measurement points 1 through 9) or large distances (greater than about 20 feet shown in measurement points 50 through 60), data averaging via rotation of the tool face, while not necessary, may improve tool face to target accuracy. Such improved accuracy may be advantageous for certain applications in which the position of a relief well must be known with a relatively high degree of accuracy.

Erroneous data may also optionally be identified by comparing the dip of the magnetic interference vectors with the change in tool face to target (ΔTFT) as shown in FIGURE 10. The dip of the magnetic interference vector is theoretically less than or about equal to the change in tool face. Thus, survey points at which the dip of the magnetic interference vector is greater than the change in tool face may possibly be erroneous. FIGURE 10 plots ΔTFT and the dip of the magnetic interference vector versus the measurement number for the field test data shown in FIGURE 9. As shown, the dip values are less than the ΔTFT values except for a few measurement points (a portion of measurement points 50 through 60) at

which the distance between the hypothetical measured and target wells is large (greater than about 20 feet) and the corresponding magnetic interference vector is weak (less than 0.02 Gauss). Such a large distance and weak magnetic interference field may, in some instances, introduce error into the TFT values.

Embodiments of this invention may also be utilized in combination with other surveying techniques. For example, in applications in which the inclination of the target well is less than about 80 degrees, gravity azimuth methods, such as those described in the McElhinney patents, may be used with the passive ranging techniques described herein. Alternately and/or additionally, the magnetic field measurements may be utilized to determine magnetic azimuth values via known methods. Such magnetic azimuth values may be advantageously utilized at points along the measured well at which the magnetic interference is low, e.g., near a target well that has been sufficiently demagnetized.

In a previous application (U.S. Patent Application Ser. No. 10/369,353) the applicant discloses methods for determining azimuth via gravity and magnetic field measurements using, for example, MWD tools such as that disclosed in FIGURE 1. Referring now to FIGURES 2 and 11 (FIGURE 11 is abstracted

from U.S. Application Ser. No. 10/369,353), the lower sensor set 120 has been moved with respect to upper sensor set 110 (by bending structure 140) resulting in a change in azimuth (denoted 'delta-azimuth' in FIGURE 11). The following equations show how the foregoing methodology may be achieved. Note that this analysis assumes that the upper 110 and lower 120 sensor sets are rotationally fixed relative to one another.

The borehole inclination (Inc1 and Inc2) may be described at the upper 110 and lower 120 sensor sets, respectively, as follows:

$$Inc1 = \arctan(\frac{\sqrt{Gx1^2 + Gy1^2}}{Gz1})$$
Equation 8

$$Inc2 = \arctan(\frac{\sqrt{Gx2^2 + Gy2^2}}{Gz2})$$
Equation 9

where G represents a gravity sensor measurement (such as, for example, a gravity vector measurement), x, y, and z refer to alignment along the x, y, and z axes, respectively, and 1 and 2 refer to the upper 110 and lower 120 sensor sets, respectively. Thus, for example, Gx1 is a gravity sensor measurement aligned along the x-axis taken with the upper sensor set 110. The artisan of ordinary skill will readily recognize that the gravity measurements may be represented in unit vector form, and hence, Gx1, Gy1, etc., represent directional components thereof.

The borehole azimuth at the lower sensor set 120 may be

described as follows:

$$BoreholeAzimuth = ReferenceAzimuth + DeltaAzimuth \qquad \text{Equation 10}$$

where the reference azimuth is the azimuth value at the upper sensor set 110 and where:

5

$$DeltaAzimuth = \frac{Beta}{1 - Sin((Inc1 + Inc2)/2)} \qquad \text{Equation 11}$$

and:

$$Beta = \arctan\left(\frac{(Gx2 * Gy1 - Gy2 * Gx1) * \sqrt{Gx1 * Gy1 * Gz1}}{Gz2 * (Gx1^2 + Gy1^2) + Gz1 * (Gx2 * Gx1 + Gy2 * Gy1)}\right) \qquad \text{Equation 12}$$

Using the above relationships, a surveying methodology may be established, in which first and second gravity sensor sets

10   (e.g., accelerometer sets) are disposed, for example, in a drill string. As noted above, surveying in this way is known to be serviceable and has been disclosed in U.S. Patent 6,480,119 (the '119 patent).   In order to utilize this methodology, however, a directional tie-in, i.e., an azimuthal

15   reference, is required at the start of a survey.   The subsequent surveys are then chain referenced to the tie-in reference. For example, if a new survey point (also referred to herein as a survey station) has a delta azimuth of 2.51 degrees, it is conventionally added to the previous survey

20   point (e.g., 183.40 degrees) to give a new azimuth (i.e., borehole azimuth) of 185.91 degrees.   A subsequent survey point having a delta azimuth of 1.17 degrees is again added to the previous survey point giving a new azimuth of 187.08 degrees.

25

If a new survey point is not exactly the separation distance between the two sensor packages plus the depth of the previous survey point, the prior art recognizes that extrapolation or interpolation may be used to determine the reference azimuth.

5 However, extrapolation and interpolation techniques risk the introduction of error to the surveying results. These errors may become significant when long reference chains are required. Thus it is generally preferred to survey at intervals equal to the separation distance between the sensor

10 sets, which tends to increase the time and expense required to perform a reliable survey, especially when the separation distance is relatively small (e.g., about 30 feet). It is therefore desirable to enhance the downhole surveying technique described above with supplemental referencing,

15 thereby reducing (potentially eliminating for some applications) the need for tie-in referencing.

The '353 application provides a method for utilizing supplemental reference data in borehole surveying

20 applications. The supplemental reference data may be in substantially any suitable form, e.g., as provided by one or more magnetometers and/or gyroscopes. With continued reference to FIGURES 2 and 11, in one embodiment, the supplemental reference data are in the form of supplemental

25 magnetometer measurements obtained at the upper sensor set 110. The reference azimuth value at the upper sensor set 110,

may be represented mathematically, utilizing the supplemental

magnetometer data, as follows:

$$ReferenceAzimuth = \arctan(\frac{(Gx1*By1-Gy1*Bx1)*\sqrt{Gx1^2+Gy1^2+Gz1^2}}{Bz1*(Gx1^2+Gy1^2)-Gz1*(Gx1*Bx1-Gy1*By1)})$$

<div align="right">Equation 13</div>

5

where Bx1, By1, and Bz1 represent the measured magnetic field

readings in the x, y, and z directions, respectively, at the

upper sensor set 110 (e.g., via magnetometer readings). The

borehole azimuth at the lower sensor set 120 may thus be

10   represented as follows:

$$BoreholeAzimuth = \arctan(\frac{(Gx1*By1-Gy1*Bx1)*\sqrt{Gx1^2+Gy1^2+Gz1^2}}{Bz1*(Gx1^2+Gy1^2)-Gz1*(Gx1*Bx1-Gy1*By1)})+...$$

$$...\frac{Beta}{1-Sin((Inc1+Inc2)/2)}$$ Equation 14

15   where Beta is given by Equation 12 and Inc1 and Inc2 are given

by Equations 8 and 9, respectively, as described previously.

It will be appreciated that the above arrangement in which the

upper sensor set 110 (FIGURES 1 through 3B) includes a set of

20   magnetometers is merely exemplary. Magnetometer sets may

likewise be disposed at the lower sensor set 120. For some

applications, as described in more detail below, it may be

advantageous to utilize magnetometer measurements at both the

upper 110 and lower 120 sensor sets. Gyroscopes, or other

25   direction sensing devices, may also be utilized to obtain

supplemental reference data at either the upper 110 or lower

31

120 sensor sets.

It will also be appreciated that the above discussion relates
to the generalized case in which each sensor set provides
5   three gravity vector measurements, i.e., in the x, y, and z
directions. However, it will also be appreciated that it is
possible to take only two gravity vector measurements, such
as, for example, in the x and y directions only, and to solve
for the third vector using existing knowledge of the total
10   gravitational field in the area. Likewise, in the absence of
magnetic interference, it is possible to take only two
magnetic field measurements and to solve for the third using
existing knowledge of the total magnetic field in the area.

15   While the passive ranging techniques described herein require
only a single magnetometer set (e.g., located at the upper
sensor set as in the above example), it will be appreciated
that passive ranging may be further enhanced via the use of a
second set of magnetometers (i.e., a first set of
20   magnetometers at the upper sensor set and a second set of
magnetometers at the lower sensor set). The use of two sets
of magnetometers, along with the associated accelerometers,
typically improves data density (i.e., more survey points per
unit length of the measured well), as shown in the examples
25   described above, reduces the time required to gather passive

ranging vector data, increases the quality assurance of the generated data, and builds in redundancy.

It will be understood that the aspects and features of the present invention may be embodied as logic that may be represented as instructions processed by, for example, a computer, a microprocessor, hardware, firmware, programmable circuitry, or any other processing device well known in the art. Similarly the logic may be embodied on software suitable to be executed by a processor, as is also well known in the art. The invention is not limited in this regard. The software, firmware, and/or processing device may be included, for example, on a down hole assembly in the form of a circuit board, on board a sensor sub, or MWD/LWD sub. Alternatively the processing system may be at the surface and configured to process data sent to the surface by sensor sets via a telemetry or data link system also well known in the art. Electronic information such as logic, software, or measured or processed data may be stored in memory (volatile or non-volatile), or on conventional electronic data storage devices such as are well known in the art.

The sensors and sensor sets referred to herein, such as accelerometers and magnetometers, are presently preferred to be chosen from among commercially available sensor devices that are well known in the art. Suitable accelerometer

packages for use in service as disclosed herein include, for example, Part Number 979-0273-001 commercially available from Honeywell, and Part Number JA-5H175-1 commercially available from Japan Aviation Electronics Industry, Ltd. (JAE).

5 Suitable magnetometer packages are commercially available called out by name from MicroTesla, Ltd., or under the brand name Tensor (TM) by Reuter Stokes, Inc. It will be understood that the foregoing commercial sensor packages are identified by way of example only, and that the invention is not limited

10 to any particular deployment of commercially available sensors.

Although the present invention and its advantages have been described in detail, it should be understood that various

15 changes, substitutions and alternations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims.

ABSTRACT

A method for surveying a borehole is provided. The method includes providing a tool having a magnetic field measurement device disposed thereon and positioning the tool in a borehole. Magnetic interference vectors are determined at at least two positions in the borehole by comparing the measured magnetic fields at those positions with a known magnetic field of the earth. The magnetic interference vectors indicate a direction to a target subterranean structure. Various embodiments of the invention compare the directions to the target subterranean structure with a historical survey thereof, so as to determine a distance between the borehole and the subterranean structure and an azimuth of the borehole. The surveying methodology of this invention may advantageously improve borehole surveying data obtained, for example, in relief well and/or well twinning drilling applications.

FIG. 1

110

100

120

154
150

158
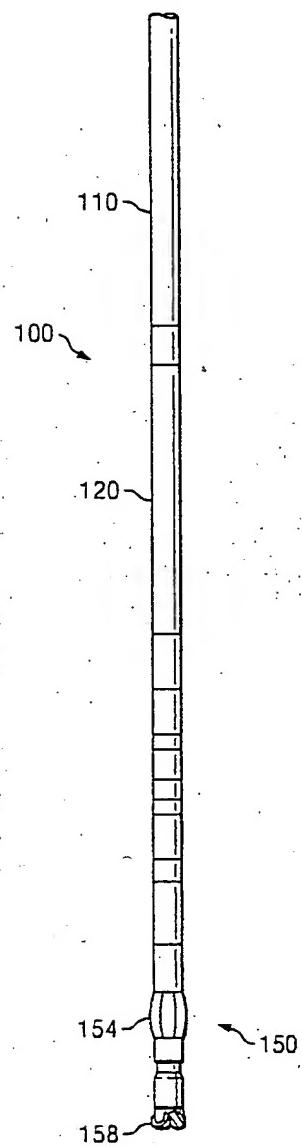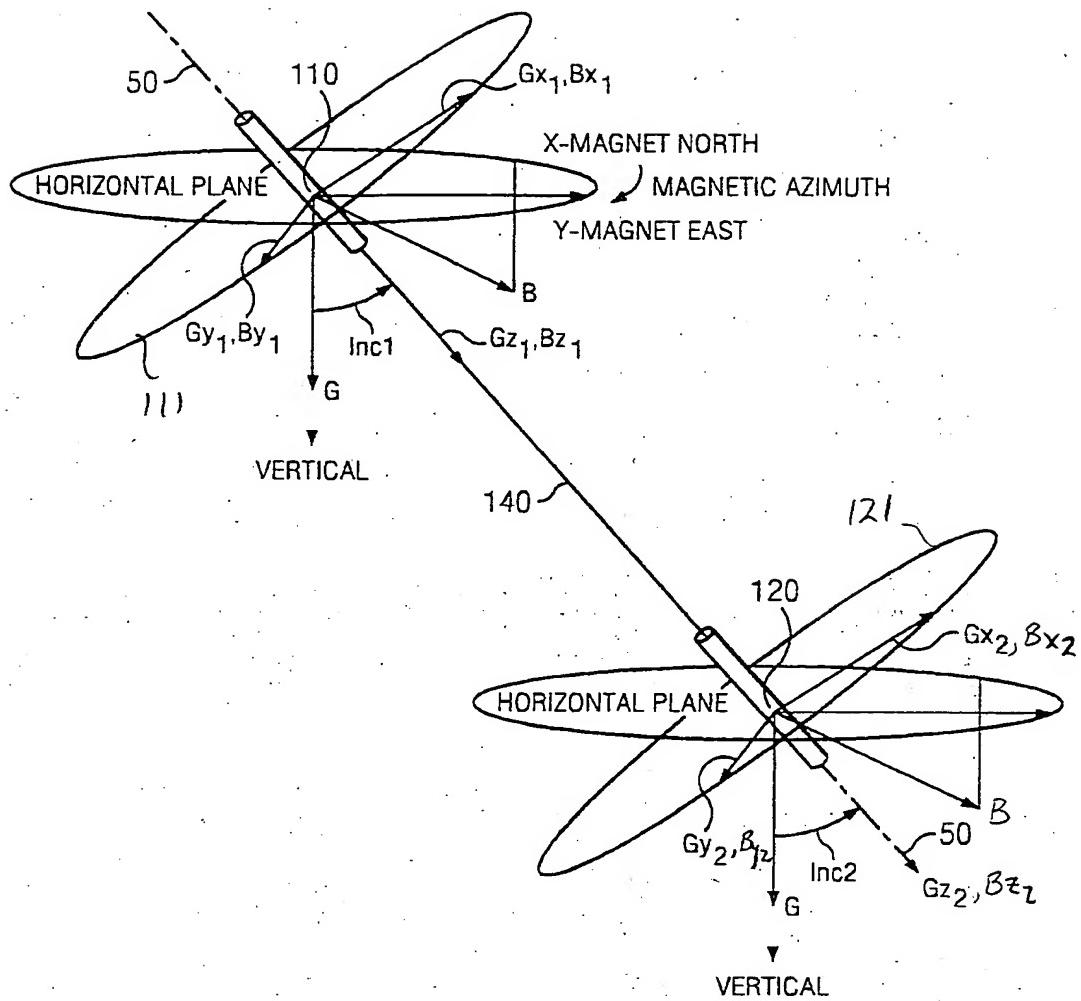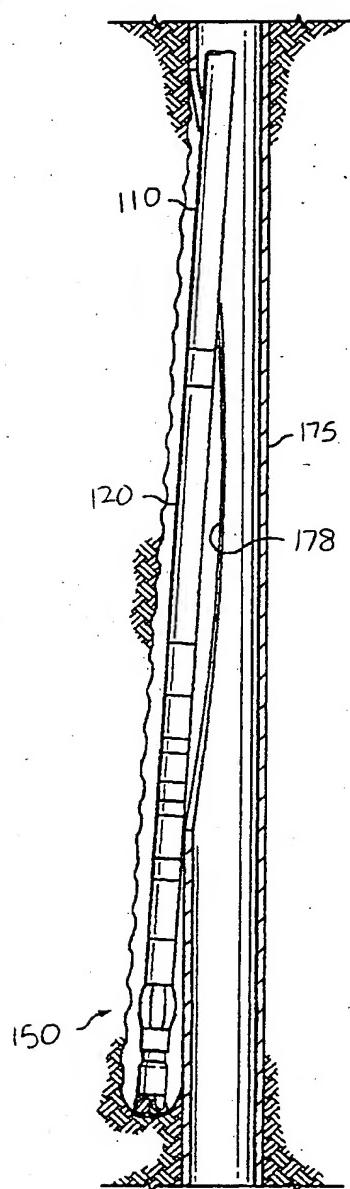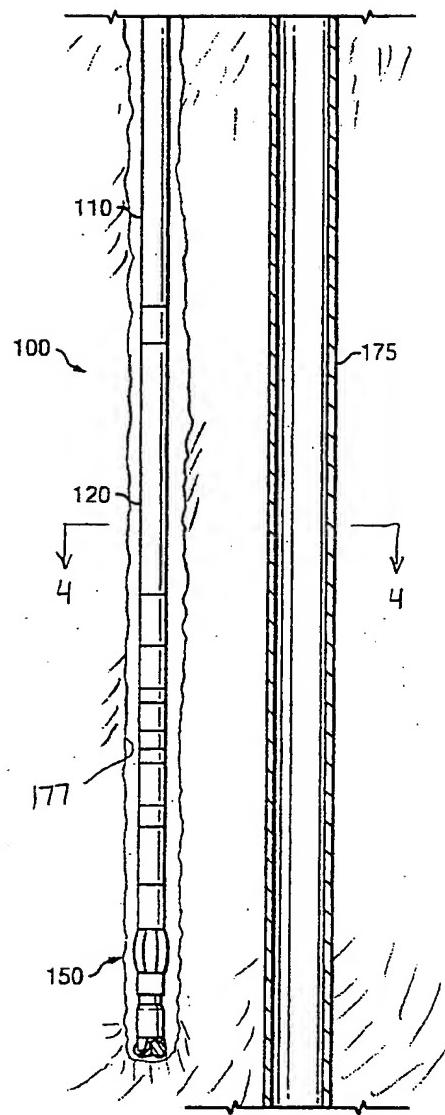
FIGURE 1

FIGURE 2

FIGURE 3A

FIGURE 3B.
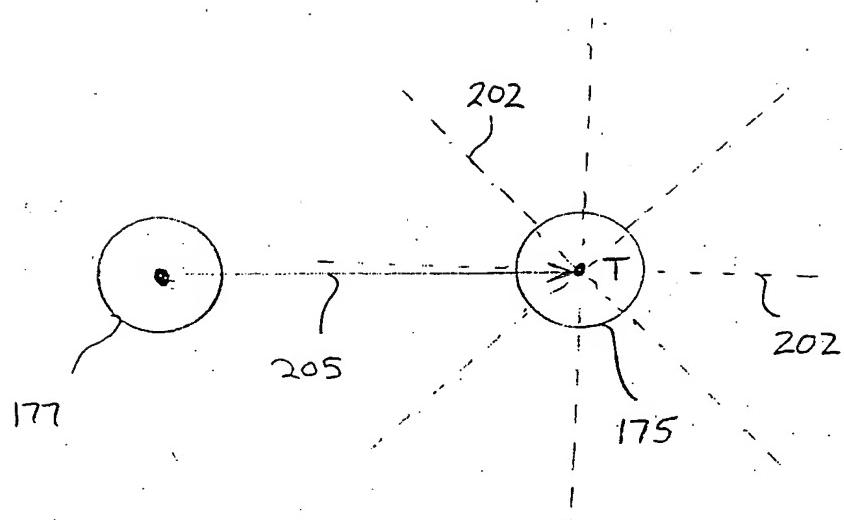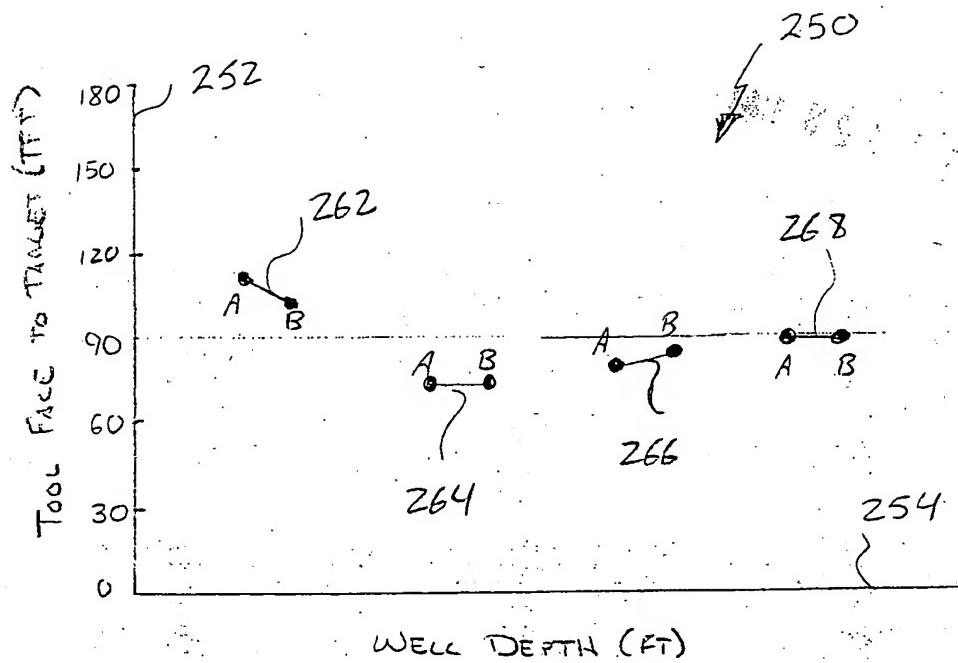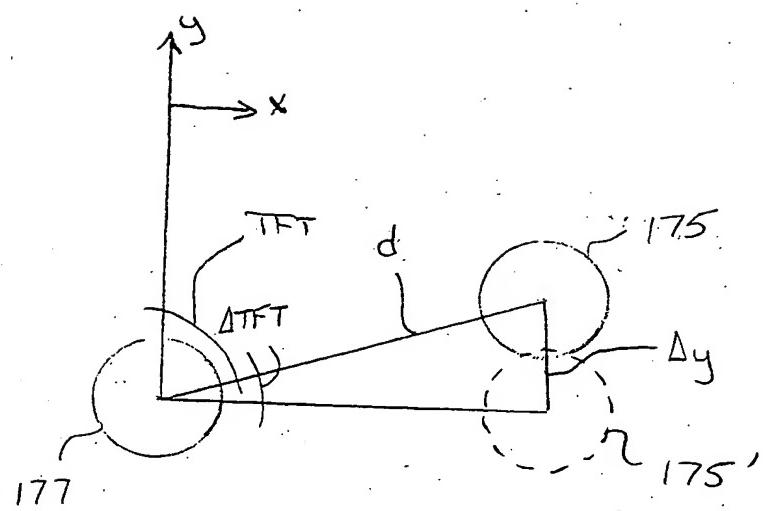
FIGURE 4

FIGURE 5

FIGURE 6

TF from Tool to Target
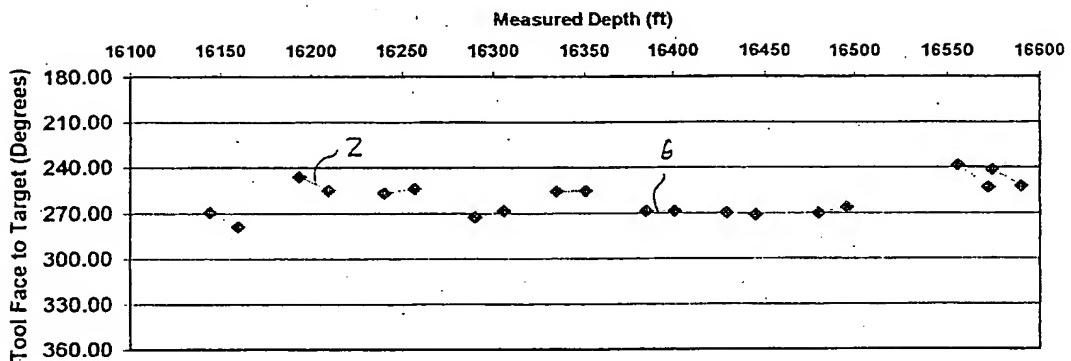
FIGURE 7

9/12

Azimuths of Measured and Target Wells

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11